Extraplanar Emission-Line Gas in Edge-On Galaxies

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ABSTRACT

Seven edge-on galaxies were imaged in Hα in order to determine if extraplanar emission-line gas (as seen in NGC 891) is a common feature of spiral galaxies. Four of the seven were found to have prominent filamentary extraplanar structures with typical Hα luminosities of 1037-1038 erg S-l and scales of 1–2 kpc. Unlike NGC 891, none of the galaxies had an extensive emission-line halo, to within the sensitivity of the observations, approximately 24 mag/square arcsec in I{a-–morc than five times fainter than the diffuse emission of NGC 891.

Subject headings: Galaxics: Interstellar Matter, Galaxies: Individual (NGC 973, NGC 4302, NGC 5403, NGC 5777, UGC 2092, UGC 3326, UGC 12281)

1. Introduction

Recent observations of the nearby edge-on galaxy NGC 891 reveal an extraplanar medium full of filaments and bubbles of ionized gas as well as an extensive diffuse medium (Pildis et al. 1993, Keppel et al. 1991, Dettmar 1990, Rand et al. 1990). The similarity of NGC 891 with the Milky Way (van der Kruit 1984) implies that our Galaxy might have similar amounts of emission-line gas outside its plane and that both diffuse and filamentary ionized gas might be a common feature of spiral galaxies,

The search for extraplanar ionized gas in other nearby edge-on spirals has given ambiguous results. Rand et al. (1992) found faint filaments in NGC 4631, and no extraplanar emission in NGC 4565. Dettmar (1993) also studied those two galaxies--confirming the lack of activity in NGC 4565 and the extraplanar emission near the nucleus of NGC 4631- --plus two others. He found that NGC 5775 has filamentary structures emerging from its disk, while NGC 4244 had no extraplanar emission. None of the galaxies in either study were found to have the extensive diffuse emission seen outside the plane of NGC 891.

in this study, we observed seven edge-on galaxies likely to have active star formation, and thus good candidates for having ionized gas outside their disks. We used IRAS detections as a selection criterion (further details of the selection criteria are in Section 2.1). Imaging in Hα revealed that over half of the seven galaxies we observed had filaments or other prominent emission-line structures emerging from their disks, but none had extensive diffuse gas to the limits of our observations. Details of the imaging and initial reduction are in Section 2.2, results of the imaging are described in Section 3. Spectroscopy proved not to be very enlightening; see Sections 2.3 and 4. Section 5 contains discussion of the results and conclusions.

2. Observations

All observations were made at the Michigan-Dartmouth-MIT (MDM) Observatory on Kitt Peak, Arizona.

2.1. Selection Criteria

The galaxies in this study were selected from a catalog generously provided by M. Roberts. The catalog contains all UGC galaxies with major axis $\geq 3'$ and axial ratio (major axis/minor axis) ≥ 5. From this catalog we chose galaxies accessible at MDM Observatory during our scheduled observing runs that appeared edge-on in the Palomar Sky Survey prints, A further selection criterion is that the galaxies had been detected in the far infrared (FIR) by IRAS and have a relatively high value of the FIR surface brightness, $\log(\mathrm{FIR}/a^2)$, where a is the major axis of the galaxy in arcminutes and $\log(\mathrm{FIR})$ is from the "IRAS Extragalactic Catalog" (Fullmer & Lonsdale 1989). To observe the maximum number of galaxies possible during our observing runs required us to loosen the constraints on observing galaxies with the highest values of $\log(\mathrm{FIR}/a^2)$; the galaxies span an order of magnitude in that quantity. The basic properties of the galaxies we observed are listed in Table 1. The galaxies' velocities and dimensions as listed in that table were obtained from NED,[1] and are slightly different than the values listed in the UGC that were used to select these systems.

Two galaxies (NGC 4157 and NGC 5301) were found after imaging to be not sufficiently

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[1]The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California institute of Technology, under contract with the National Aeronautics and Space Administration.

edge-on to be analyzed for extraplanar structures and thus arc not included in Table 1. One galaxy (UGC 12506) had an incorrect velocity in its NED listing (now corrected), so the Hα filter used to image it did not encompass Hα_{galaxy}. It, too, is excluded from Table 1.

2,2. Imaging

The edge-on galaxies were imaged using the KPNO narrow-band Hα filter set and a Cousins broadband R filter. There were two separate observing runs: one in May 1991 using the 1.3 m McGraw-Hill Telescope and a Thomson 400 x 576 pixel CCD (0.46″/pixel), and onc in October 1991 using the 2.4 m Hilter Telescope and a TI-4849 398 x 598 pixel CCD on the BRICC 135 mm camera (Luppino 1989) (0.25″/pixel). Table 2 lists the run each galaxy was observed, the central wavelength and full-width-half-maximum of the KPNO Hα filter used, and the number and length of exposures in Hα and R.

The 2.4 m telescope allows onc to rotate the camera so that the long axis of the CCD was aligned with the plane of the galaxy being imaged. Despite this, the small field of view with this telescope and CCD— 1.7' x 2.5', versus 3.1' x 4,4' obtained with the 1.3 m and Thomson CCD—required us to image the galaxies in two parts. This is noted in Table 2.

The images were reduced using standard IRAF packages and calibrated using standard stars observed by Massey et al. (1 988). The Hα images were coaddcd to produce a master frame for each galaxy position, then the R band frame for that position, scaled so that the stars in it were the same magnitude as those in the coadded Hα frame, was subtracted from that master Hα frame.

2.3, Spectroscopy

Spectroscopy of some of the imaged galaxies was obtained under nonphotometric conditions in October 1991 using the Hiltner Telescope and the BRICC camera as described above, The projected slit width was 1.68″, giving a spatial scale of 0.728” pixel-l and a dispersion scale of 2.27Å $pixel^{-1}$. With the slit positioned along the long axis of the chip, the wavelength range covered was 5700 -6900Å. Table 3 lists the galaxy and a description of the slit position used, along with the number and length of exposures. When angular distances from the nucleus are used in ~'able 3, they are distances as measured along the plane of the galaxy, with a direction such as "N" used only as an indication of the side of the galaxy that was observed.

Only one of the galaxies (NGC 5777) had been imaged previously and found to have emission-line gas outside of its plane. The other galaxies were imaged in the same October 1991 run, after the spectroscopy, so spectra were taken near the nucleus perpendicular to the planes of the galaxies, rather than along any features, as was clone with NGC 5777. These galaxies were selected on the basis of their appearance in the Palomar Sky Survey prints rather than on their Hα properties, thus some spectra were taken of galaxies that proved to have no extraplanar features (NGC 973, for example), The spectra were reduced using standard IRAF packages.

3. Results—Imaging

Two of the seven galaxies we imaged (NGC 973 and NGC 5403) have no visible extraplanar emission-line structures to the limits discussed below in Section 3.6. The five remaining galaxies exhibit extraplanar gas and arc discussed below.

To obtain magnitudes for the extraplanar structures we found in the other galaxies, we used the PROS package in IRAF, which allows for background subtraction and user-clrawn polygonal apertures, both crucial for measuring the brightness of irregularly-shaped faint objects. The magnitudes thus obtained are combined Hα+[NII] magnitudes, since the KPNO Hα filters arc broad enough to include the [NII] doublet. Since we do not have spectroscopy of the emission-line features of any of the galaxies in our sample, we cannot make a reasonable conversion from filter magnitudes to Hα magnitudes; thus, all magnitudes and luminosities in this paper will bc the total for the filter, unless stated otherwise. In addition, no corrections are made for dust extinction in the host galaxies since the dust content of the emission-line features of these galaxies is not well known. The magnitudes arc corrected for Galactic extinction.

3.1. UGC 12281

UGC 1228] has two extraplanar emission-line features: two discrete clouds emerging on the north side of the galaxy (Fig. 1) ant] a clumpy plume emerging from the south side (Fig. 2). Note that these features arc on opposite sides of the galaxy's plane.

The northern feature forms an angle of 43° with respect to the plane, and points towards the center of the galaxy. The centers of the two clouds are 9.9" apart, or 1.4 kpc at the assumed distance to UGC 12281 of 30 Mpc (v = 2559 km/s; $H_0 = 85$ km/s Mpc^{-1} is used throughout this paper). The upper cloud is 13.3" (1.9 kpc) above the plane of the galaxy. The filter magnitude of the upper cloud is 19.86 ± 0.06, which corresponds to a luminosity of 2.86--3.16 $\times 10^{38}$ crg s^{-1}, while the brighter lower cloud has a magnitude of 19,45 $\pm$ 0.03 and a luminosity of 4.30--4.54 $\times 10^{38}$ erg S-l. When taken as a whole, the structure's brightness is within] .5σ of the sum of the brightnesses of the upper and lower Clouds, suggesting that the two clouds are discrete entities rather than merely brightness enhancements in a continuous plume.

The southern feature, while clumpy, appears to bc a plume rather than separate clouds. The plume extends 7.7" (1.1 kpc) from the plane of the galaxy at an angle of 51°, pointing away from the center of the galaxy. The two main clumps in the plume are 2.9" (0.41 kpc) apart. The magnitude of the plume is 20.55 $\pm$ 0.09, which implies a luminosity of 1.46-1.7'2 $\times 10^{38}$ erg s^{-1}.

3.2. NGC 5777

NGC 5777 is the first galaxy we found with a prominent extraplanar plume, yet no sign of diffuse extraplanar gas (Figure 3). The plume extending out of NGC 5777 is on the SE side of the galaxy. It appears to emerge from a bright 1111 region above the plane, and it curves away from the center of the galaxy, It is 9.1" x 3.1", which is equivalent to 1.1 kpc x 0.38 kpc at the assumed distance to NGC 5777 of 25 Mpc (v = 2145 km/s). The filter magnitude of the plume is 20.82 $\pm$ 0.16, and the filter magnitude of the 1111 region immediately beneath the plume is 19.31 $\pm$ 0.05. These correspond to luminosities of 7.51–10.1 $\times 10^{37}$ erg s^{-1} and 3.40-3.66 $\times 10^{38}$ erg s^{-1}, respectively.

3.3. UGC 3326

UGC 3326 has a single faint plume on its SW side (Fig. 4). The plume is relatively straight and points away from the center of the galaxy at an angle of 52° to the plane. At the end of the plume, there is a relatively bright, cloud-like structure. The plume is 5.7" long and 1.1-2.0" wide (narrower at the bottom of the plume, wider at the top), which at a distance of 48 Mpc (v = 4085 km/s) is equivalent to 1.3 kpc long by 0.26-0.47 kpc wide. Since the plume is so faint, its filter magnitude and luminosity are relatively uncertain; the magnitude is 21.09–21.44 and the luminosity is 1,74-2.40 $\times 10^{38}$ crg s^{-1}.

3.4. NGC 4302

NGC 4302 has an extremely faint emission-line structure emerging from the plane close to the nucleus of the galaxy. Figure 5 is an image of the galaxy smoothed with a gaussian of σ = 2.5 pixels = 1.15", which makes the plume easier to find. The plume extends 11.5" out of the plane, which is equivalent to 0,73 kpc at the assumed distance to NGC 4302 of 13 Mpc (v = 1108 km/s). It is 2,8" (0.18 kpc) wide and appears to be straight and perpendicular to the plane of the galaxy. As with the plume in UGC 3326, the plume in NGC 4302 has a fairly uncertain magnitude clue to its faintness; its magnitude is 20.65-21.78, which corresponds to a filter luminosity of 0.96--2.74 x 10^{37} erg s-l.

3.5. UGC 2092

UGC 2092 has a bubble-like structure *in* the plane on the NE side of the galaxy (Fig. 6). This structure may indeed be a superbubble, but is equally likely to be an HII region partially blocked by foreground dust in the plane of the galaxy. The diameter of the structure is 7.0", 2.4 kpc at an assumed distance to UGC 2092 of 72 Mpc (v = 6120 km/s). It has a filter magnitude of 19,463:0.05, which corresponds to a luminosity of 2.31--2.52 $\times 10^{39}$ erg s^{-1}.

3.6. Diffuse Extraplanar Light

The galaxy with the most extensively studied extraplanar emission-line structures such as plumes and bubbles, NGC 891, also has prominent diffuse emission-line gas extending far out of the plane. The diffuse emission in NGC S91 has been found to $|z| > 4$ kpc, along with filaments as long as 2 kpc (Dettmar 1990, Rand et al. 1990). In addition, bubbles 0.5 kpc in diameter with filter magnitudes of up to 17-18 have been found emerging from that, galaxy's disk (Pildis et al. 1993). One question we wished to answer with this study is whether any other edge-on galaxies besides NGC 891 have either or both of these features.

As stated above, we detected Hα plumes in over half of the edge-on galaxies we imaged. However, none of the galaxies had any diffuse extra.planar emission to within $3\sigma_{\mathbf{sky}}$. Table 4 lists the upper limits on the surface brightness of any diffuse light in magnitudes per square arcsecond. For comparison, the brightness of a typical region of the diffuse extraplanar gas in NGC 891 is 22.1 magnitudes per square arcsecond. Note that the aberrantly high value for NGC 4302 is due to the short exposure time for that galaxy (see Table 2). The $3\sigma_{sky}$ upper limits are quite conservative; the average surface brightness immediately above and below the galaxies (where one would expect any diffuse emission-line gas to be) is within $1\,\sigma$ of the average surface brightness of the sky far from the galaxies.

4. Results–Spectroscopy

The spectroscopy of the edge-on galaxies suspected of having extraplanar emission-line gas produced a null result; the more sensitive imaging showed that none of the galaxies had diffuse extraplanar gas. However, even the spectrum of NGC 5777- -the one galaxy that was known to have an emission-line plume emerging from its disk—did not have sufficient signal to obtain any velocity information about its plume. Future investigations of the velocity structure of the plumes and filaments described in Section 3 will require more sensitive observations.

5. Discussion and Conclusions

Four of the seven edge-on galaxies we investigated had kiloparsec-scale emission-line structures emerging from their disks, while none of the seven had diffuse gas even one-fifth as bright as that seen in NGC 891. If this latter result is combined with those of Dettmar

(1993) and Rand ct al. (1992), none of the eleven edge-cm galaxies surveyed have the same sort of extensive diffuse extraplanar emission as NGC 891, which is usually portrayed as a typical spiral galaxy, while six of the galaxies had filamentary or patchy structures outside their disks. More typical, perhaps, than NGC 891 with its bright diffuse extraplanar emission with embedded filaments is a galaxy with no diffuse 1041< gas outside its disk, and zero or one emission-line plume reaching a kiloparsec out of its plane.

The Hα luminosities of these plumes-1037 to 1038-–arc comparable to those of HII regions of very massive single stars and the brightest HII regions in dwarf irregular galaxies and some Sa–Sab galaxies (Kennicutt 1988). Thus, the energy required to ionize the plumes is reasonably small, although the mechanism to form kiloparsec-scale structures above the plane of a spiral galaxy is not well-known

If diffuse extraplanar emission is rare and kiloparscc-scale emission-line filaments arc relatively common, then the next question to answer is under what conditions spiral galaxies will produce these filaments, Our initial criterion-the far-infrared surface brightness log(IrIR/a^2)---appcars not to correlate with the presence of extraplanar structures. With the addition of the galaxies studied by Dettmar (1993) and Rand ct al. (1992) as well as NGC 2820, NGC 4656, and NGC 5907 (Rand, private communication) to our sample, wc attempted to find some galaxy-wide quantity that would predict the existence of these extraplanar filaments. None of the quantities examined- far-infrared surface brightness, far-infrared luminosity, blue luminosity, far-infrared to blue luminosity ratio, and axial ratio-–was an accurate predictor of the existence of extraplanar structures in a galaxy. For example, NGC 891 and NGC 973 arc both luminous in the far-infrared ant] blue bands and have similar axial ratios, but NGC 891 has both diffuse emission and many filaments while NGC 973 has no apparent extra.planar emission. Furthermore, UGC 12281 is onc of the dimmest galaxies in the sample by all the quantities mentioned above, yet it is one of the most active galaxies in our sample in terms of extraplanar structure. It may be true that extraplanar structures are easier to detect in galaxies with very high axial ratios such as UGC 12281 (r = 11 .7) because these "superthin" galaxies (Goad & Roberts 1981) are closest to being perfectly edge-on, but structures are also seen in galaxies with low axial ratios such as NGC 891 (r = 4.7) and NGC 4302 (r = 5.5).

NGC 891 has both an extensive radio continuum halo (Allen et al. 1978) and the first X-ray halo to be detected in a normal spiral galaxy (Bregman & Pildis 1993). These may both be correlated to the presence of extensive 10^4 K gas in the low halo. Of the seven galaxies we observed, all but UGC 12281 were surveyed by Hummel et al. (1991) and only NGC 4302 and NGC 5403 were found to have extended emission at 4.8 GHz. Since these two galaxies have faint to no extra.planar structures, as well as no detectable diffuse emission, the existence of a radio continuum halo seems not to be a universal indication of extraplanar emission-line activity. ROSAT observations of edge-on spirals have just begun, but preliminary results seem to indicate that few spiral galaxies have an extensive X-ray halo like NGC 891. This is similar to the findings of Hummel et al. (1991) on radio continuum halos of edge-on spirals: only 5.5% of the 181 galaxies they surveyed had significant radio halos. The existence of these three types of emission halos-- X-ray, Hα, and radio continuum—in NGC 891 may not be coincidence. One explanation of why NGC 891 has an extensive diffuse Hα halo is that the high pressure of its X-ray halo compresses the emission-line gas and thus increases its emission measure (which is proportional to $n_e{}^2$, where n_e is the electron density). Galaxies without an X-ray halo may have roughly the same mass of 10^4 K gas as does NGC 891, but the gas may be at too low a density to have been detected in our survey.

Our observations indicate that NGC 891 is not a typical edge-on galaxy in that it has an extensive emission-line halo (as well as X-ray and radio continuum halos) and none of the other galaxies we observed had one. Approximately half of all the galaxies examined in Hα have kiloparsec-scale filaments emerging from their disks. Spectroscopy of these filaments to find line ratios and the velocity structure of the filaments has yet to be done sucessfully, but would help in explaining the origin, nature, and life cycle of these filaments. This, in turn, could perhaps answer the question of why half of the edge-on galaxies observed have no filaments at all. A further question to be answered is why NGC 891 is different from all the other edge-on galaxies observed, and if the Milky Way is similar to it after all.

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'1'able 1: Basic galaxy properties

Galaxy Name	Velocity (km/s)	a (Major Axis)	Axial Ratio	log(FIR)[a]	log(FIR/a^2)
NGC 4302	1108	5.5'	5.5	-12.4	-13.9
NGC 5403	2741	3.1'	3.4	-12.6	-13.6
NGC 5777	2145	3,1'	7.8	-12.9	-13.9
UGC 12281	2559	3.5'	11.7	-13.4	-14.5
NGC 973	4851	3.7'	7.4	-13.0	-14.1
UGC 2092	6120	3,2'	10.7	-13.6	-14.6
UGC 3326	4085	3.5'	17.5	< -13.1	< -14.2

[a]FIR is in units of W/m^2

Table 2: Observing log for imaging

Galaxy Name	Side	Date	Filter λ_0	Filter FWHM	Hα Exposures	R Exposures
NGC 4302	–	May 1991	6606A	76Å	1 X 1800 S	1 × 1100 s
NGC 5403	–	May 1991	6606A	76Å	2 x 1800 s	1 x 1200 s
NGC 5777	·	May 1991	6606A	76Å	2 X 1800 S	1 X1200S
UGC 12281	N	Ott 1 991	6606Å	76Å	5 X 9 0 0 S	1 × 900 s
UGC 12281	s	Ott 1991	6606A	76Å	4 X 9 0 0 S	1 × 900 s
NGC 973	NE	Ott 1991	6649Å	80A	4 × 900 s	1 × 900 s
NGC 973	SW	Oct 1991	6649Å	80Å	4 X 9 0 0 S	1 × 900 s
UGC 2092	N	Oct 1991	6693Å	83Å	4 X 9 0 0 S	1 × 900 s
UGC 2092	s	Ott 1991	6693Å	83Å	4 X 9 0 0 S	1 X 9 0 0 S
UGC 3326	NE	O t t 1991	6649Å	80A	4 X 9 0 0 S	1 × 900 s
UGC 3326	Sw	Ott 1991	6649Å	80Å	4 X 9 0 0 S	1 × 900 s

Table 3: Observing log for spectroscopy

Galaxy Name	Slit Location	Exposures
NGC 5777	along plume	11×900 s
UGC 12281	$\perp$ to plane, 30" S of nucleus	4×900 s
"	$\perp$ to plane, 1' s of nucleus	4X900S
"	-L to plane, 30" N of nucleus	4×900 s
"	$\perp$ to plane, 1' N of nucleus	4×900 s
NGC 973	-L to plane, 30" S of nucleus	4×900 s
"	$\perp$ to plane, 30" N of nucleus	4×900 s
UGC 3326	$\perp$ to plane, 30" W of nucleus	4×900 s
"	$\perp$ to plane, 30" E of nucleus	7×900 s

Table 4: Upper limits on diffuse extraplanar light in edge-on galaxies

Galaxy Name	$3\sigma_{\rm sky}$ Upper Limit
NGC 4302	22.8 mag/sq. arcsec
NGC 5403	24.1 mag/sq. arcsec
NGC 5777	23.9 mag/sq. arcsec
UGC 12281	24.2 mag/sq. arcsec
NGC 973	24.2 mag/sq. arcsec
UGC 2092	24.0 mag/sq. arcsec
UGC 3326	24.1 mag/sq. arcsec

Fig. 1.— N side of UGC 12281: the center of the galaxy is towards the bottom. The two discrete emission-]ine clouds are indicated. The horizonal line at the bottom of the figure is 30" (4.4 kpc) long.

Fig. 2--- S side of UGC 12281: the center of the galaxy is towards the top. The plume is indicated. The horizons] line at the bottom of the figure is 30" (4.4 kpc) long.

Fig. 3---- NGC 5777: N is up and E is to the left. The plume emerging from the plane of the galaxy is indicated. The horizons] line at the bottom of the figure is 30" (3.6 kpc) long.

Fig. 4.-- SW side of UGC 3326: the center of the galaxy is towards the top. The faint plume is indicated. The horizons] line at the bottom of the figure is 30" (7.0 kpc) long.

Fig. 5--- Gaussian smoothed (σ = 1,1 5") image of NGC 4302: N is up and E is to the left. The plume is indicated. The horizonal line at the bottom of the figure is 30" (1.9 kpc) long.

Fig. 6--- NE side of UGC 2092: the center of the galaxy is towards the bottom. The bubblelike emission-line structure is indicated. The horizons] line at the bottom of the figure is 30" (10 kpc) long.